

Optimal Recycling for Printed Wiring Boards (PWBs) in India

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Abstract

Electronic waste or e-waste recycling in India is mainly motivated by the recovery of value contained in the PWBs (printed wiring boards), which is retrieved by extracting precious metals (mainly gold, silver, palladium) with wet chemical processes, involving highly toxic substances such as mercury and cyanide. These works are done by untrained people, resulting in a high impact on their health and the environment. In contrast to this practice, in Europe, valuable metals from relevant e-waste fractions are recovered efficiently in large industrial integrated smelters and refineries with profit margins allowing for environmentally safe handling of the critical substances.

This study shows that the Indian informal sector generates a high environmental impact, as a relatively large amount of chemicals are used for the extraction and are subsequently emitted to the environment without any treatment, while only recovering a significantly smaller fraction of the value contained in the test material compared to an integrated precious metal smelter and refinery.

The results provide preliminary figures allowing for proposing new business models to divert certain fractions from the informal sector to dedicated industrial smelters, increasing the profitability of all stakeholders and simultaneously substantially relieving environmental burden and safety and health issues.

Keywords: e-waste, precious metals, recycling, MFA, business models, environmental impact.

1 Introduction

E-waste recycling is economically motivated by its content in base, precious and special metals, while it carries an environmental burden due to its load in substances of concern (Hagelüken, 2006a). In India, where no specific law regulates e-waste recycling yet, the existing system has developed organically from the pre-existent scrap industry traditionally dealing with scrap from ship breaking, end-of-life vehicles or demolition waste (Sinha-Khetriwal et al., 2005). Because of a lack of control and regulation of the recycling industry, the poorest strata of the population find an economic benefit in recovering the valuable parts of e-waste with non-scientific methods while simply dumping the non profitable and often hazardous fractions. Moreover, toxic chemicals are used to recover valuable metals like gold, silver or copper from the printed wiring boards, causing a direct impact to the workers' health and to the environment (e-waste guide, 2007; Greenpeace, 2005; Agarwal et al., 2003). In this

context, the recycling of electronic waste is motivated by economic gain only, with no regard towards social and environmental concerns, and is managed by a largely informal sector (Puckett et al., 2002). Though this sector makes its living out of these hazardous processes, they do not know how efficient the recovery of precious metals is, and what potential there is for improvement.

In developed countries like Switzerland, where recycling practices are regulated and where experience and awareness concerning environmental issues are high (SAEFL, 2004), the collection and recycling of e-waste is an intentionally developed and organised system (Sinha-Khetriwal). Based on Extended Producer Responsibility (EPR), the system guarantees a safe recycling of *all* e-waste, providing a convenient solution to the consumers. Financial sustainability is assured by an Advanced Recycling Fee (ARF) on the one hand, which guarantees that non-valuable fractions are treated correctly, and by state-of-the-art technology on the other hand, allowing a maximal recovery of the value (Hagelüken, 2006a, 2006b).

The objective of this paper is to study the efficiency of precious metal recovery from PWBs for the two scenarios, wet chemical leaching ('hydrometallurgy') in the Indian informal sector and smelting ('pyrometallurgy') in a precious metal refinery in Europe. As it is suspected that the European scenario is more efficient, the results should allow determining if the increased recovered value allows to divert critical operations from the informal sector in India by triggering market leverages. In other words, is it possible to offer more money to Indian recyclers for some waste fractions than what they would gain by processing them in hazardous operations?

This paper offers to describe and quantify both processes by applying Material Flow Analysis (MFA), which has proven to apply to developing countries where access to data is difficult (Binder, 2001). The results of the MFA will allow on the one hand to measure and compare the efficiency of both scenarios, and to categorise the emissions to the environment on the other hand. The latter will allow to estimate and compare the environmental impacts, though a complete Life Cycle Assessment (LCA) is not possible with current data.

2 Method

In order to be able to compare the two scenarios, the following definitions are necessary:

- The chosen functional unit (FU) for the comparison is "the disposal of 1t of PWBs". The material processed during the study is Pentium II motherboards without the processor.
- The system boundaries are defined in Figure 1. In this case, the pre-treatment consists of shredding the boards into pieces of about 4 cm² to make homogeneous samples. A loss of 5 % of the material is admitted during the shredding, which is justified by the experimental conditions¹. Other processes studied are the transport and the material

¹ This loss is caused by the difficult local conditions for sampling during the investigation. However, in professionally executed sampling operations at an industrial precious metals refiner with appropriate equipment and experienced staff, any material loss is thoroughly avoided, since sampling is conducted to get a very accurate picture (weight and composition) of the original material.

recovery. For each process, an inventory of resource and energy consumption and emissions is made. The resource and energy needed to manufacture and prepare the inputs are excluded of the study's domain.

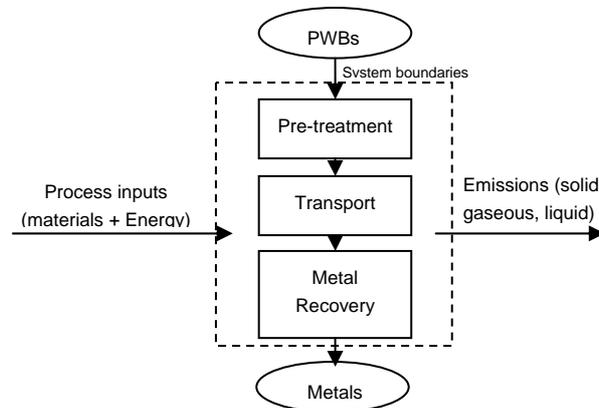


Figure 1: *system boundaries of the present study*

The two scenarios compared are the wet chemical recovery of gold in the Indian context, and an alternate scenario where the PWBs would be exported to a state-of-the-art integrated smelting and metals refining plant in Europe, based on the model of the Umicore Precious Metal Refinery (UPMR).

The Indian wet chemical process's pre-treatment consists of manual segregation of apparent gold parts and the rest of the printed wiring board. Transport is considered as being negligible, as the e-waste is purchased locally. The metal recovery is done through a complex chemical chain of reactions involving acids such as cyanide. Several wet chemical processes for extraction of gold are used, depending of the concentration of gold contained in the raw material. The cyanide process is the most common observed process for materials with low concentrations of gold in the India informal sector. An alternate process for "richer" material is based on mercury. A detailed description of these two processes is available on-line (Keller, 2006).

For the smelting/refining process, no other pre-treatment is considered than the shredding described above, as improper mechanical pre-processing may cause up to 20% losses of precious metals (Hagelüken, 2006a). The transport distance here is the shipping distance by cargo from Mangalore in India to Antwerp in Belgium² (location of UPMR). The recycling operation is streamlined along two processes: the Precious Metal Operations (PMO) focus on

² Mangalore is the closest harbour to the experimental area located in Bangalore. The shipping distance is considered to be 10'400 km.

fast throughput and maximised yields at optimised costs, and are tuned for the efficient refining of complex and valuable raw materials containing precious metals. The Base Metals Operations (BMO) focus on flexibility and cost-efficient processing of by-products from the PMO. It is the combination of both BMO and PMO that allows the recovery of above 95% of the valuable metals (Hagelüken, 2006a, 2006b).

The Indian scenario was studied (Keller, 2006) empirically with a group of informal recyclers in the city of Bangalore. Mass and/or volumes of inputs and outputs were measured if possible at every step. Non-measurable flows are then estimated in order to balance the mass flows (Brunner & Rechenberger, 2004). Some samples of chemical substances were not directly identifiable, and were sent to a laboratory for analysis.

The smelting / refining scenario is described and quantified based on literature and communications with the staff from the UPMR.

3 Results

3.1 Material Flow Analysis

The Indian wet chemical process using cyanide is described in the flowchart in Figure 2. The flows represented here show the PWBs in [kg] and the related content of gold in [g]. This allows to identify losses of gold, thus to measure the efficiency of the process.

- Based on analysis (Keller, 2006), 1 ton of PWBs are considered to contain 200 ppm of gold, equivalent to 200 g.
- As per operational conditions, 5% of material and gold are lost during the shredding and dismantling. This fraction is simply swept into the street, or more often left around the workshop and carried away by the wind or the rain.
- A manual segregation separates the nude printed boards from the pieces containing apparent gold (called “connectors” here). The nude PWBs are usually sold to other informal groups, who will burn or leach them to recover the copper (e-waste guide, 2007). This process is not considered here, as it is beyond the scope of this study. Nevertheless, this pathway causes the major loss of the gold, which is embedded in the remaining components and the layers of the boards.
- About 370 kg of ‘connectors’ remain and are treated in the leaching process. A significant fraction of the remaining gold is lost during this extraction process itself, due to the presence of many other metals, not allowing the chemicals to react specifically with the gold. Moreover, leaching processes only work on the surface of materials, encapsulated metals (e.g. within ceramic or plastic layers) are not reached.

- The gold extraction process calls for important amounts of inputs, mainly water (75 % of the input), coal (10 %) and chemicals (15 %), which are directly emitted into the environment without any treatment after usage. The liquid effluents produced contain 3 kg of metals in total in solution and are spilled into the drain. Gas emissions are caused by the burning of coal and the evaporation of the reactive solution while heating. These operations are conducted in small units without proper ventilation and the workers are directly exposed to the emissions.
- The metal scrap (367 kg) is usually thrown away and dumped in the street, sometimes sold as metal scrap in case of large amounts, which is quite rare at the scale of informal units.
- All side streams from the process still contain significant amounts of gold. The overall efficiency of the gold recovery is at a maximum of 25 %.
- It can be assumed that losses of other precious metals like palladium or silver are even much higher than those for the gold. Computer boards usually contain about 1000 ppm of silver and 100 ppm of palladium³. palladium is mainly embedded in ceramic components (multi layer capacitors) and interboard layers.

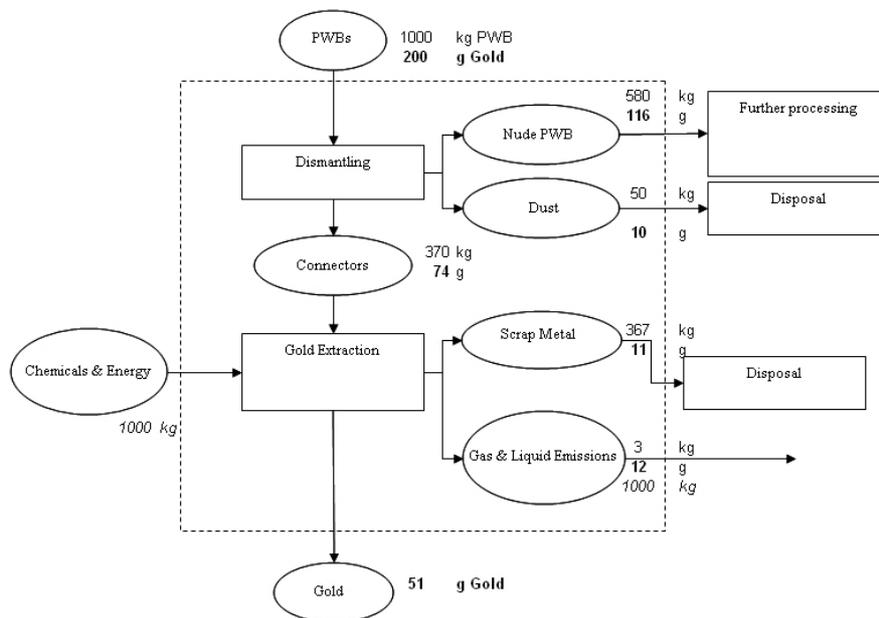


Figure 2: material flows of PWBs in the cyanide wet chemical process.

³ current Pd price is ca. 10 USD/g

The smelting / refining scenario is described in the flowchart in Figure 3. As for the previous figure, the flows of PWB parts are expressed in [kg], and the related gold flows are in [g].

- As for the previous scenario, the initial material contains 200 g of gold, a loss of 5 % in sampling is assumed here as well, although in practice – if shredding and sampling takes place at UPMR and not under Indian conditions, this loss would not occur.
- The undesired fraction is here considered to be nil, as no specific fraction has been extracted to be treated separately.
- The emissions due to transport result from the shipping from India to Europe. These emissions were estimated using the data from the Ecoinvent database (ecoinvent, 2007).
- The solid waste stream is concentrated in a poor slag, mainly composed of Mg, Al, Ca, Si and Fe in an oxidised form (Hagelüken, 2006b). This inert, depleted slag produced in UPMR is used as additive for concrete production and as construction material, so that no solid material needs to be landfilled.
- Studies made by UPMR have shown that the organic fraction of the PWB contained the sufficient feedstock energy needed for the smelting and refining of the valuable metals. Moreover, some energy is even produced in excess and re-used in the plant (Hagelüken 2007). Hence, being a metallurgical process in the first step, no additional material is required and the only input to the smelting process are the PWBs⁴. In the subsequent hydrometallurgical metals purification steps, small amounts of well controlled chemical reagents are used in closed systems.
- Submitted to severe environmental regulations and equipped with state-of-the-art emission control technology, only 10 grams of metals in total are emitted to the air and water.
- 17 precious, special and base metals are recovered during this process, with an overall efficiency exceeding 90 %! Almost 4 times more gold is recovered than in the previous scenario, recovery rates for palladium and silver also exceed 95%.

⁴ In practice, the Umicore smelter always treats a mix of different recycling materials, out of which circuit boards/e-scrap account for about 10%. Other materials in this mix are e.g. catalysts, anode slimes and other residues from the metallurgical industry. These materials are blended in such a way that optimum treatment conditions exist with regard to smelting temperature, slag formation, energy input, metals distribution etc.

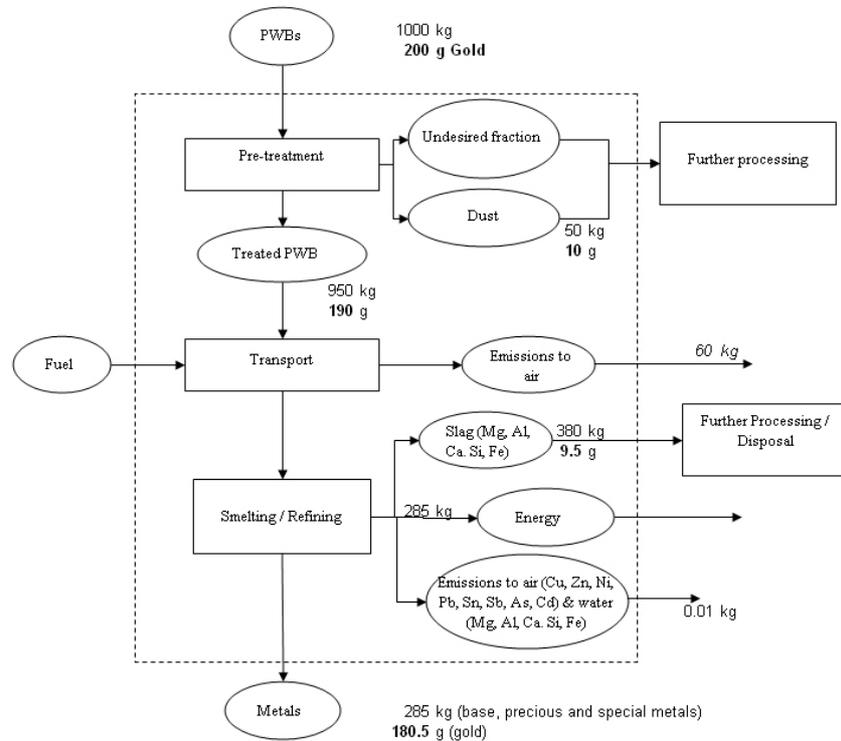


Figure 3: material flows of PWBs in the smelting / refining scenario.

3.2 Cost / Benefit Analysis

The results provided by the material flow analysis, together with information recollected during interviews with the workers from the informal sector, allow to estimate the cost / benefit balance for both scenarios. The following simple equation is used to calculate the value added by recycling 1 ton of PWBs for the two scenarios:

$$\text{Total Profit} = \text{Sales of Recovered Metals} - \text{Total Operational Costs} - \text{Total Transport Costs}$$

In the case of the wet chemical recovery of gold, the benefits result from the sales of the recovered gold and the nude printed boards sold to other units for copper recovery. The operational costs are induced by the price paid for the various inputs to the process and the wages paid to the workers.

For the smelting / refining scenario, the revenues are calculated based on the sales of four major metals, i.e. gold, silver, copper and palladium (Art, 2006). The costs are generated by

the price⁵ of operations of the UPMR plant (all costs included), and the shipment of the material to Europe.

The economic balance for each scenario is presented in the table below:

	wet chemical leaching	smelting / refining
sales of recovered metals	1'300	4'600
transport costs	--	600
operational costs	800	1'000
profit	500	3'000

Table 1: cost / benefit analysis for the two scenarios in [€] per ton PWBs

The cost / benefit analysis shows that the smelting / refining scenario generates up to six times more profit than the wet chemical leaching of gold!

4 Discussion

Though the results of the material flow analysis don't allow for a thorough life cycle inventory, the following conclusions may be stated about the environmental impact of the two scenarios:

- The wet chemical leaching process induces important inputs of resources and energy, directly emitted to the environment after usage, while the smelting / refining scenario is almost "self-sufficient" from a material flow perspective. Moreover, some of these inputs to the wet chemical leaching contain very toxic chemicals such as cyanide and mercury.
- The totality of the non-valuable solid fraction is dumped into the environment in the first scenario, while in the second additional metals like lead, tin, nickel, antimony, bismuth etc. are recovered. Non-recoverable ones like iron or aluminium are transferred to a slag and re-used as construction material
- The amount of metals emitted directly to air and water is 300 times higher in the first scenario.
- The emissions due to the transport by cargo of the material from India to Europe is negligible. However, the impact generated by road transport, locally for the first scenario and to the closest shipping harbour in the second, could be significant and shouldn't be neglected.

⁵ The word "price" is used here, as the model UPMR applies is a so called "toll-refining" model, where the service of smelting and refining the PWBs is billed, while the value extracted is returned to the owner, either as metals, either as money at metal market price.

A proper life cycle analysis (LCA) would allow to make a scientific comparison of the two scenario's environmental impact per category of impact. Nevertheless, the results of the present study show that the difference in material flows emitted to the environment between the two scenarios is such, that it is possible to safely state that the smelting / refining scenario has by far a better environmental performance. It is questionable at this point, looking at the difficult experimental conditions, whether it is worth investing in a proper LCA to exactly determine the environmental impact of these two scenarios.

The cost / benefit analysis has shown that applying state-of-the-art technology generates up to six times more revenue. Both ends of the recycling chain could benefit from this added value if new business models were to be implemented: a higher price could be offered to the workers of the informal sector in India for the unprocessed PWBs than the revenue they currently generate by processing PWBs themselves, thus creating an economic incentive to stop the practice of hazardous operations. Nevertheless, some barriers to the implementation of this win-win situation remain:

- Informal units usually operate at very small scale, with a material turnover of a few 100 kg per month, while an integrated smelter and refiner such as UPMR can treat economically only larger lots of several tons. This means that a "buffer" would be necessary between both ends, who could gather these smaller flows into larger batches. Such an intermediate should have the financial capacity to pay the informal units for the small amounts collected, and to wait for the payback⁶.
- It is currently unknown, what the threshold in profit increase would be for a change in business attitude i.e. what other values are built in the current scenario (being informal, thus avoiding administrative and reporting, avoiding taxes, avoiding compliance costs for social and environmental standards, ...).
- India is keen to prevent strategic metals, a prerequisite for the industrial development, from leaving the country. So far it is difficult until recently even impossible, to receive export licences for e-waste treatment abroad. However shipping e.g. PWBs from India e.g. to Europe is not critical under a resource management perspective if appropriate business models are used. A standard procedure in precious metals refining is a so called "toll refining operation", which implies that recovered precious metals can also be

⁶ It can take several months for the material to be transported to Europe, analysed and processed. This buffer could be a cooperative body, a state organisation or also a kind of "commercial broker", but it is important that the "buffer" does not take the biggest part of the additional profit, but that the informal sector really benefits from the new model (incentives!).

physically shipped back to the supplier; thus India would not lose valuable resources to Europe. In contrast, due to the higher efficiency of the industrial recycling operations, more value would be recovered.

- As e-waste can be considered as hazardous waste, some Indian and international legislations could become an obstacle: as the collection of e-waste remains in the hands of an informal economy, there is no official trace of the material collected. This could cause problems with respect to Indian environmental legislation, where the origin of hazardous wastes needs to be justified. Also, the transboundary shipping of containers of e-waste is regulated by the Basel convention, which would call for authorisations from countries at both end of the chain. Such ‘notification procedures’ in principal are not a problem, Umicore receives authorised shipments from all parts of the world, but it requires some administrative work for the Indian organisation.
- The cost / benefit analysis presented in this study widely relies on estimates made at the time of the study (Keller, 2006). Several parameters depend of variables such as the market prices of metals or the costs for international sea cargo, which could vary significantly with time. A scientifically sound decision-helping model needs to integrate these variables, in order to provide the margin available for maintaining such a win-win-situation. Taking into account the huge profit and environmental impact gap between both scenarios, however the vulnerability to parameter variances appears to be rather limited.

5 Conclusions and Recommendations

These conclusions both on the environmental and economic impacts are only valid for the type of e-waste studied, i.e. one type of computer motherboards. However the approach opens the door for defining new recycling scenarios for all categories of e-waste. In order to optimise the recycling of e-waste and to minimise the amounts of material transported across continents, further studies need to integrate several variables inherent to the material considered:

- It is necessary to determine at what concentration⁷ of precious metals it is profitable to ship e-waste, as it could be more profitable for some lower grade categories to be recycled locally, if environmentally compliant processes are available.

⁷ For computer mainboards further dismantling is not advisable, since it bears a high risk of losing valuable metals while doing so (e.g. breaking brittle ceramic parts which contain palladium and other precious metals). Also the current praxis to remove processors from boards and treat them separately is questionable, unless the processors can be reused as components. Local hydrometallurgical treatment of processors bears the same

- As a significant share of the material flow ends up in the inert slag in the smelting / refining scenario, it could be worthwhile to segregate beforehand the fractions⁸ which are not valorised such as aluminium and iron. This would minimise the quantities to transport and increase the efficiency of the material recovery process. Moreover, India has the capacity to recycle such materials.
- Alternate business models will also need to be studied for important materials contained in e-waste such as glass and plastics, which have their own critical recycling processes. The recycling market for these materials doesn't depend of the content in precious metals, but obeys to different constraints. For instance cathodic ray tubes (CRT) are phasing out of the electronics market as they are replaced by flat screens, and the production is shifting to Asia where a market remains for these items. Thus recycled CRT glass needs to be made available in China and India who could absorb the flows from markets that don't use it anymore. Also flame retarded (brominated) plastics are being phased out because of legal restrictions. Their recycling is problematic as the contamination of other plastics should be avoided, which is likely to happen in informal sectors.

This study indicates that it might be possible to use the 'best of two worlds'⁹ in order to maximise profit and resource recovery whilst minimising the environmental impact in the management of a complex hazardous waste such as e-waste. Today developing and transition countries like India and China already generate huge volumes of domestic e-scrap. The informal sector does importantly contribute to its recycling and it is paramount to increase its eco-efficiency in doing that by: a) shifting risky processes to the formal industry and b) promoting its integration in the e-waste management system.

constraints as for connectors (e.g. encapsulation of gold), while in an integrated smelting and refining process they could remain on the boards and enter the same process flow. The additional precious metals content from the processors would be clearly identified during sampling, increasing the gold content e.g. to 250 ppm and triggering a higher payment to the supplier.

⁸ Interesting in this context are monitor- and TV-boards, which contain large iron and aluminium parts, that could be removed manually in India before shipment of the upgraded boards. The same applies in principle for circuit boards from audio equipment and power supplies, as well as for hard disk and floppy disk drives (removing the circuit boards from the casing)

⁹ The 'Best of 2 Worlds' is a StEP (www.step-initiative.org) project to investigate the eco-efficiency (Huisman, 2003) of manual dismantling of domestic e-waste in China with control over all environmentally relevant fractions. The hypothesis is that the eco-efficiency of manual dismantling and segregation outperforms a purely mechanical recycling strategy.

The study shows benefits in exporting certain e-waste fractions for treatment. It does not, however, want to promote e-scrap imports from Europe, Japan and North-America for treatment by the Indian informal sector. Currently it is illegal and not a feasible mid term option since safe infrastructures allowing for sufficient control of the material flows and local operating conditions are not existing. The risk of abuse is much too high.

Internationalising waste management is a very sensitive topic, and asks for more research supporting the implementation of new business models. This could hopefully result in global waste management models, where the informal sector from developing countries would be integrated into the global economy, preserving their livelihood without deteriorating their health and environment .

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